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A Simplified Method to Calculate the EMF Characteristics of Multi-disk Axial-gap PM Motor using 2-D & 3-D FEM

Young-Kwan Kim* · Ju Lee

Abstract

The purpose of this paper is characteristic analysis of multi-disk axial-gap pm motor for turbo compressor. The axial-gap permanent magnet motor has shown a growing interest in high-speed application for its high-efficiency, compact size and low vibration characteristics due to core-less structure. To achieve high-power, the axial-gap PM motor has multi-disk structure of stator and rotor disk. Because of its complicated magnetic flux path, it is not easy to calculate a dynamic characteristics using finite element analysis. In this paper, the simplified 2-D unfolded model to predict EMF characteristic is presented. To verify thesuggested 2-D unfolded model analysis of back-EMF characteristic was calculated and compared 3-D finite element. Finally the proposed method is verified by experimental results and shows good agreement with test results.

Key Words : Multi-disk, Axial-gap PM Motor, Turbo compressor, Electro motive force, Coreless

1. Introduction

The Axial-gap permanent magnet motorshave several advantages over traditional cylindrical motors such as high-speed, high-efficiency, high-power density, and low torque ripple caused by core-less structure. Among permanent magnet motors, the axial-gap permanent magnet (AGPM) motors have shown a growing interest in high-speed applications for its thinner, lighter, lower in noise and vibration characteristic. The magnetic flux path of axial-gap motor is axial direction and the current carrying conductor of stator is in a radial direction. The high power capacity of AGPM can be obtained by multi-disk structure from increase of stator and rotor disk to axial direction.

The structure of AGPM motor in this paper consists of a thin 2 stator disk and 3 rotor disks which increase the motor output power and shown in Fig. 1. The 4 stator coils comprise two phases in one disk and each of the stator disk coils consist two parallel circuits. The rotors comprise plurality of sintered permanent magnet each rotor and back yoke to make flux path of magnetic flux on each

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side disk.

The AGPM motor features two phases on the statorand 6 poles on the rotor. Because of its complicated magnetic flux path of rotor back yoke and radial flux effect of stator coil, AGPM motor can not be calculated using 2-D approach such as done conventional cylindrical machines.

Therefore, 3-D FE analysis should be used to calculate the no-load voltage of AGPM motor. In order to calculate the characteristics such as back-EMF and torque characteristics, this work need a lot of calculation time.

In this paper, we proposed simplified analysis model which was unfolded 2-D multi-sliced x-y planeto reduce calculation time. The back-EMF waveforms are calculated using proposed model method and the results were compared 3-D FEA results and test results. According to supposed analysis model, we can obtain a good accuracy of analysis and reduce calculation time.

2. 2-D & 3-D Finite Element Analysis

2.1 Model Description

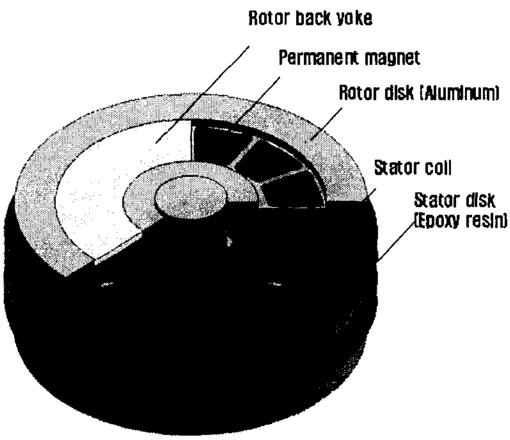


Fig.1. The cross-sectional view of multi-disk axial-gap PM motor

Fig. 1 shows the cross-sectional view of multi-disk axial gap permanent magnet motor for high-speed operation. The rotor poles were divided into two segment magnet having same polarity to make effectively use of permanent magnet flux.The 2-dimensional FEA method was proposed in previous works [1], but it could not give appropriate back-EMF waveform. In some other study, the 2-D grid model was reported and shows a good agreement with experimental results [2]. Table 1 shows specification of multi-disk AGPM motor.

2.2 Back-EMF calculation using 2-D

When a coil is wound with coreless air-gap winding, maximum flux-linkage occurs when permanent magnet pole is positioned with the axis of center of air-gap winding coils.

Table 1. Specifications of Axial-gap PM Motor

Item	Quantity	Unit
Rated power	2,000	[W]
Rated voltage	300	[V]
Rated frequency	2,350	[Hz]
Operation speed	47,000	[rpm]
Number of phase	2	-
Number of coil/phase	2	-
Number of stator disk	2	-
Air-gap length	0.5	[mm]
Number of poles	6	-
Number of segment/poles	2	-
Number of disk	3	-
Rotor outer disk diameter	74	[mm]
Number of parallel circuit	2	
Rotor disk material	AL	-
Residuals of PM	1.15	T

The phase back-EMF which derived from the rate of flux-linkage change is expressed as

$$e_p = -\frac{d\lambda}{dt} = -\frac{d\lambda}{dt}\cdot\frac{d\theta}{dt} = -\omega_r\frac{d\lambda}{dt} \qquad (1)$$

It is clear that the back-EMF of one coil can be calculated from flux-linkage of coil with the variation of angular position [3]. Hence, if the flux-linkage according to permanent magnet position is known, the back-EMF waveforms are achieved. Fig. 2 shows a stator coil arrangement of AGPM motor.

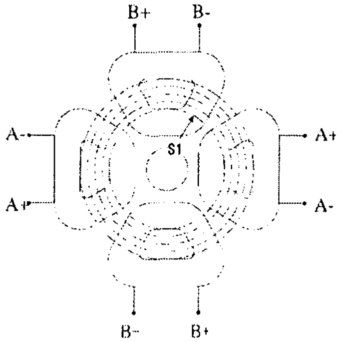


Fig. 2. Stator coil arrangement of AGPM motor

The main part of torque generationand electro-motive force of AGPM is radial length of stator coil. In order to calculate dynamic characteristics of AGPM using 2-D finite analysis, 2-D simplified models were derived using unfolded 2-D circumferential section on average stator diameter and average rotor magnet of AGPM. The unfolded 2-D model is shown in Fig. 3. And to verify this assumption, the effective length of coil side is divided 4 multi-sliced sections and the phase back-EMF can be obtained by adding the each sliced model voltage given equation in (2).

$$e_p = \sum_{i=1}^{i=4} e_i = -\sum_{i=1}^{i=4} \omega_{ri} \cdot \frac{d\lambda_i}{d\theta} \qquad (2)$$

The back-EMF in equation (1)~(2), ω_r means angular velocity of rotor and λ_i means flux-linkage of each slice. But, according to the above mentioned assumption,

$$e_p = -\frac{d\lambda}{dt} = -\frac{d\lambda}{dx} \bullet \frac{dx}{dt} = -v_x \bullet \frac{d\lambda}{dx} \qquad (3)$$

conventional 2-D approach cannot be applied from its complexity of 3-dimensional magnetic flux path. When the effective length of torque generation is divided into several slices and unfold it into x-y coordinate plane as shown in Fig. 1 and 2, the back-EMF of coil can be expressed as follows.

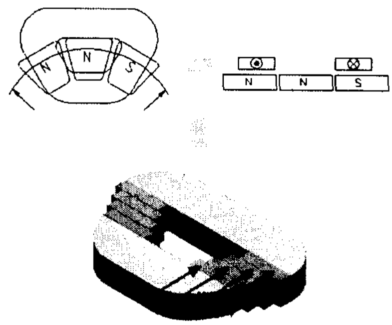


Fig. 3. Active part of Stator coil

The back-EMF of stator coil can be obtained by adding the each slice coil voltages. The total back-EMF in a stator phase winding can be given by

$$e_p = \sum_{i=1}^{i=4} e_i = -\sum_{i=1}^{i=4} \upsilon_{xi} \bullet \frac{d\lambda_i}{dx} \qquad (4)$$

where υ_{xi} is the velocity of rotor movement in x-axis of each slice and i is the effective coil length of each slice to generate electromagnetic torque.

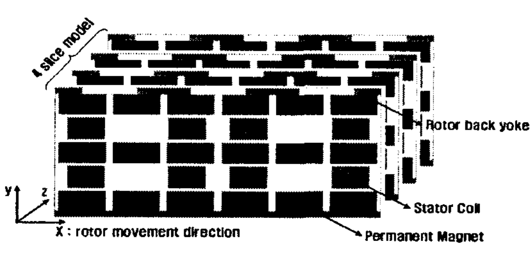


Fig. 4. Schematic drawing of the multi-sliced stator

2.3 Back-EMF calculation using 2-D

To calculate the magnetic field distribution, magneto-static field calculations at different moving part position of field variations are computed by basic Maxwell's equation:

$$rot(\gamma rot(A)) = -J_0 + rot\ M \qquad (5)$$

where γ means reluctivity of magnetic circuit, A is magnetic vector potential, $-J_0$ is the current density and M is the magnetization of permanent magnet, respectively. The stator and rotor is divided into 4 slice model of x-y segments with an equal z-directional height. Fig. 4 shows a schematic drawing of the multi-slice model. The rotor of permanent magnet and rotor back yoke are moved on their x-axis.

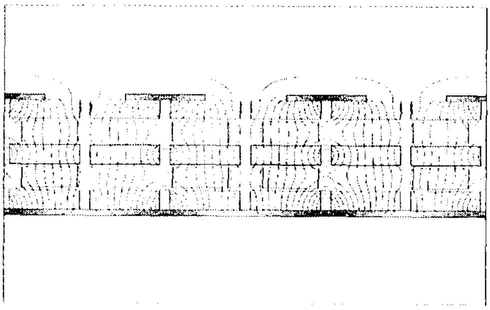


Fig. 5. 2-D FEA flux lines for unfolded model

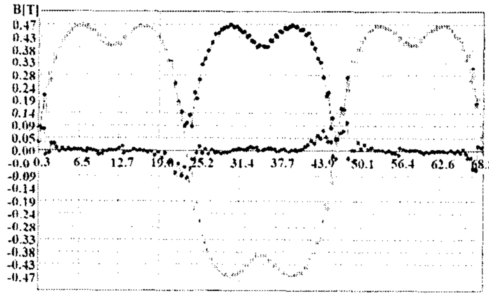


Fig. 6. Air-gap flux density

According to above mentioned unfolded 2-D analysis method, we have performed the 2-D FEA with x-directional movement. The velocity of each slice model in x-direction can be calculated considering the angular velocity and its rotor radius. It means that peripheral velocity of mean radius r1~r4 in Fig. 3 is calculated using angular velocity of rotor. In order to compare the analysis results between 2-D unfolded slice modeland 3-D model, we selected three different radius of model. In case of rotor angular velocity of 10,000[rpm], the x-directional velocity of each slice is shown Table 2.

Table 2. Peripheral Velocities of Each Slice Model for 2-D Analysis

Item		Radius [mm]	Peripheral Velocity[m/sec]
Summation of 4 sliced model	Slice 1	19.4	6.47
	Slice 2	21.5	7.17
	Slice 3	23.6	7.87
	Slice 4	25.7	8.57
Single Segment		22.6	7.53
Magnet Center		21.4	7.13

Fig. 7 shows the 3-D FEM mesh model and the flux density of multi-disk AGPM motor. In this work, the eddy current generated in the rotor material of aluminum was not considered for convenience and the influence of magnetic saturation in the rotor back yoke is neglected.

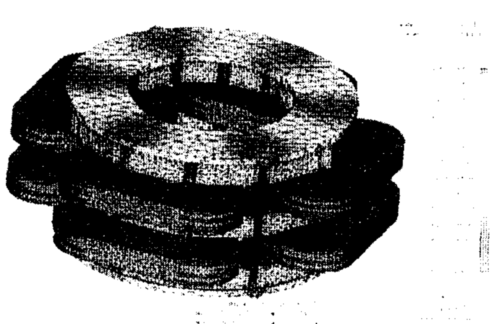


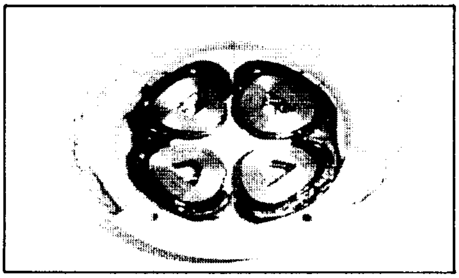
Fig. 7. 3-D mesh model of multi-disk AGPM motor

2.4 Characteristic Comparisons of Analysis and Test results

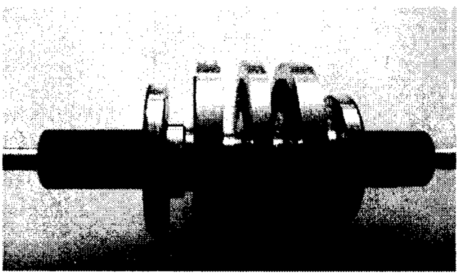
The inner-most diameter of rotor magnet of

AGPM motor asshown in Fig. 2 and Fig. 3 is slightly smaller than that of inner-most stator coil S1, depicted in Fig. 2. Usually, when the rotor stack length is larger than that of stator core, the back-EMF increase to some extent. Therefore, to make clear the effectiveness of magnet overhang (MOH) concept in AGPM motor, we designed the rotor magnet shape as show in Fig. 3.

The Fig. 8 shows stator and rotor disk of AGPM motor and Table 3 shows the test experimental results of peak back-EMF with rotor speed variation. According to the test result, the back-EMF constant is nearly constant due to coreless structure.



(a) Stator



(b) Rotor disk

Fig. 8. The multi-disk Axial-gap PM motor

Table 4 compares back-EMF calculation results and test result. The 3-D analysis shows good agreement not only its accuracy but also its waveform with test results. In case of 2-D analysis, the multi-sliced model shows low [%]Error.It can be noted from the analysis and test results that the 2-D model analysis and 3-D model are very close to the experimental results and especially 4-multi-sliced model analysis values show good agreement with 3-D and test results.As a consequence, the 4 multi-sliced 2-D models are very helpful in designing of AGPM. Fig. 9, 10 show the 2-D and 3-D analysis and test result of back-EMF waveform at 10,000[rpm].

Table 3. Experimental Results of Back-EMF

Speed [rpm]	Peak Back-EMF [V]	EMF Constant [V.sec/rad]
2,000	9.0	0.0411
3,000	13.0	0.0407
5,000	21.8	0.0416
8,000	34.4	0.0411
10,000	43.0	0.0409
47,000	198.0	0.0402

Table 4. Comparison of Test Results and 2-D, 3-D Analysis

Item	2-D Analysis			3-D Analysis	Test result
	#1	#2	#3		
Back-EMF[V]	42.3	44.1	50.7	43.4	43.0
[%] Error	1.63[%]	2.56[%]	17.9[%]	0.93[%]	-

#1 : 4 multi-sliced model
#2 : Single-segment of coil motor
#3 : Magnet-center model

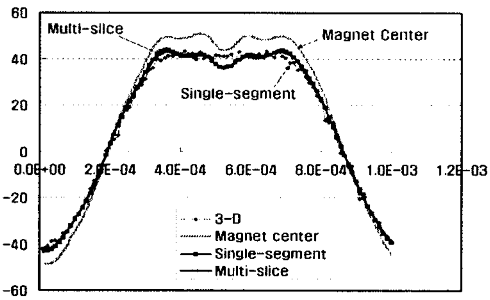


Fig. 9. Back-EMF waveform of 2-D & 3-D analysis

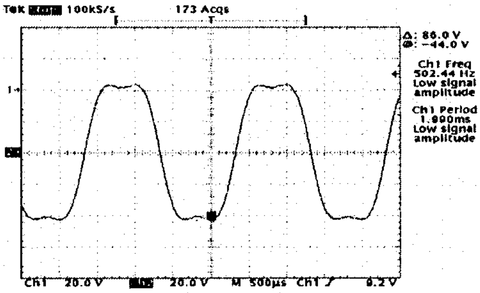


Fig. 10. Back-EMF waveform of test result

3. Conclusion

In this paper, the unfolded 2-D multi-sliced FEA model method has been investigated. The back-EMF analysis using 2-D multi-slice model of AGPM motor of shows good agreement with test results. It is found that the suggested simplified method is very helpful to predict the characteristic of axial-gap permanent magnet motor having coreless structure.

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Biography

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He received his B.S., MS degree in Electrical Engineering from Hanyang University, Seoul, Korea, in 1990, and 1992, respectively. He is in the Ph.D course in the department of Electrical Engineering, Hanyang University. His research is focused on the analysis and the optimal design with the permanent magnet motor.

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